

Light Loss in Y-11 Optical Fiber

Howard Budd^{*} and Jesse Chvojka[†]

MINERvA Note 001

November 2004

Abstract

The MINERvA experiment will use optical fiber for light collection. This fiber travels from the scintillator to the photosensor and must be bent along the way. We examined light loss of fiber for different diameters of bending and determined minimum bending diameters. A selection must be made between 1.2 mm and 1.5 mm fiber as either may be used in the experiment. We found a minimum diameter of 2'' for 1.2 mm fiber and 2.5'' for 1.5 mm fiber.

Introduction

Wavelength-shifting (WLS) optical fiber will be used in the MINERvA experiment at Fermi National Accelerator Laboratory (FNAL) for light collection in scintillator. The major concern in selecting fiber is ensuring sufficient light is collected from the scintillator and then transmitted to the photomultiplier tube (PMT).

Light loss in fiber results from several effects: attenuation of light as it travels in the fiber, geometric light loss from bending the fiber, cracks in the fiber, and optical couplings of the fiber to another medium. These effects must be understood so the appropriate fiber can be selected. We studied the effect of geometric light loss and observed some of the results of cracks in the fiber.

We tested Y-11 (green) WLS S-35, J-type fiber made by Kuraray. The three candidate fibers had the following characteristics.

<u>Diameter</u>	<u>Dye Concentration</u>
1.2 mm	175 ppm
1.2 mm	300 ppm
1.5 mm	175 ppm

^{*} University of Rochester

[†] University of Rochester

In this study, we measured only 1.2 mm, 300 ppm fiber and 1.5 mm, 175 ppm fiber. We chose these particular fibers since dye concentration should not affect flexibility and 1.2 mm, 300 ppm fiber was in greater supply than 1.2mm, 175 ppm fiber.

Methods

Before fiber can be tested, it has to be properly prepared by polishing the readout end and darkening the other end. There are several problems that this procedure solves. One problem arises from using cladded fiber. Cladded fiber means the fiber has at least one layer of material around a central core, although the fiber we tested had two layers of cladding. When cutting cladded fiber, the cladding layers can get torn in unpredictable ways. The other problem is that if the fiber cannot make a flat, flush contact with the light mixer, then that contact will have unpredictable consequences.

To solve this, a cylindrical piece of plastic called a ferrule was glued with Bicon 600 optical epoxy to the end of the fiber such that there was a small amount of fiber, roughly 1 cm, protruding from the end of the ferrule. The hole in the ferrule must be drilled out so the fiber will fit. A diamond polisher cleaved off the end of the ferrule and left a smooth, polished surface.

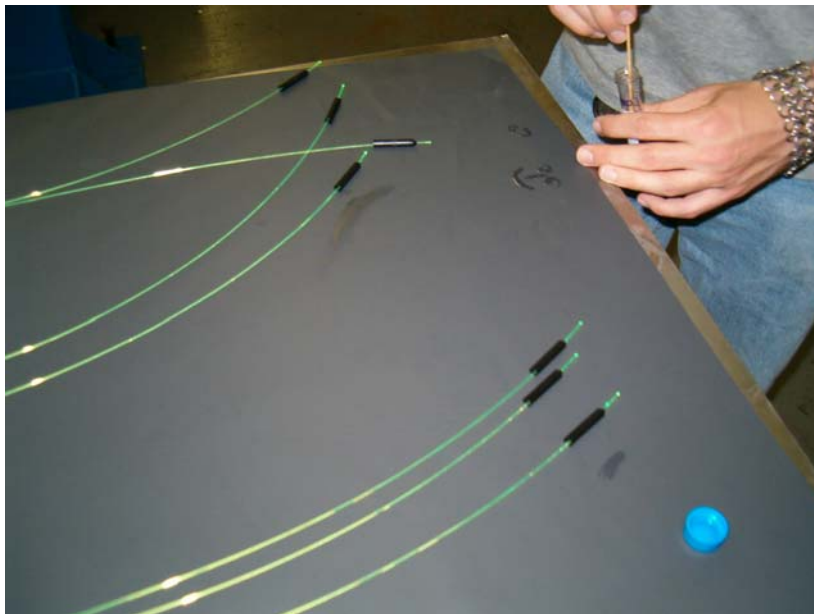


Figure 1. Above: Fiber being glued into ferrules

The other end of the fiber was cut at a 45° angle and covered with black enamel paint. This was done since it was an easy, reproducible way to stop light that would otherwise would hit the scintillator and undergo a reflection from that surface.



Figure 2. Above: A ferrule

We performed the tests in a dark box. Inside the dark box, the ferrule end of the fiber was attached to a “cookie” which is a plastic piece that provides a solid contact between the polished end of the fiber and a light mixer. A light mixer, which is a diffusing piece of plastic, was glued to a PMT and served to disperse the light from the fiber evenly before hitting the surface of the PMT. We used a R580-17 model PMT, made by Hamamatsu, 1-1/2” diameter, 10-stage, bialkali photocathode, head on type. The other end of the fiber is fed into a tile. The tile is a 1/2”x4”x4” piece of scintillator with a fiber groove in the center of one of the broad sides. The broad ends of the tile were covered with Tyvek and the narrow sides were painted with white titanium dioxide paint. All of this was wedged between 4”x4” pieces of plastic that protected the soft scintillating material from scratches and provided solid contact between the scintillator and the Tyvek. We used separate tiles for tests with 1.2 mm fiber and 1.5 mm fiber. This was necessary since different diameter fibers required different diameter grooves in the tile.

The signal was generated by gamma decays from a 1.9 milliCurie Cesium 137 source Compton scattering in the tile scintillator. A lead cone is a 4”x4”x2” piece of lead with a cone carved out of the center, which collimated the source. The cone formed a 60 degree angle with respect to the base and was 1.435” wide at the base. The cone was centered directly on the tile. The source fit into a groove directly centered on the top of the hollow portion of the lead cone.

The current from the PMT was measured with a picoammeter which was read out by the slow5 DAQ, a DOS based program.

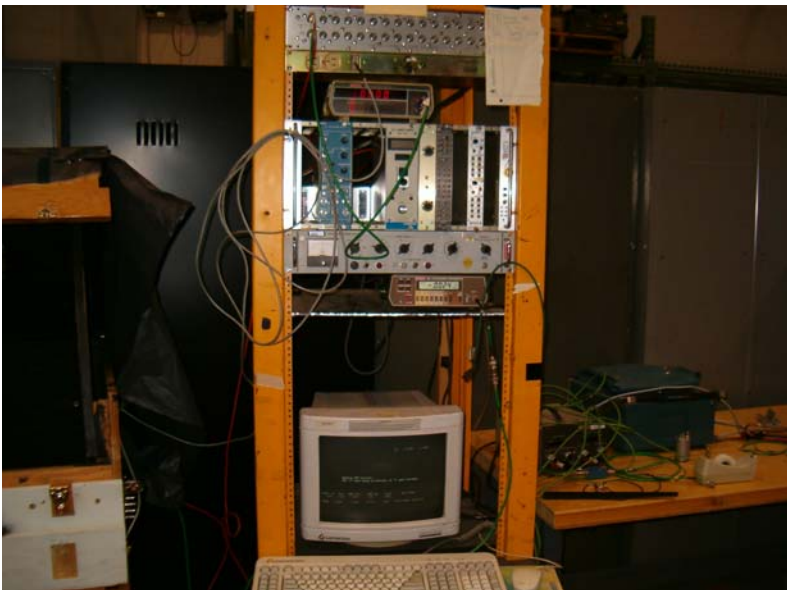


Figure 3. Above left: The dark box used in the tests
Figure 4. Below left: The electronics rack used in the tests including the picoammeter

To perform the tests, we wrapped the fiber around a cylinder of a given diameter. We used the following diameters: 1.5", 2", 2.5", 3.5", and 4.5". The fiber was wrapped 1/4, 1/2, 1, or 2 times around a given diameter. For the 1.5 mm fiber, two full wraps around a diameter were not done due to the length of the fiber. We used a control fiber during the tests to check the stability of the setup. A control fiber is prepared exactly like the fiber being tested, except it is never bent. We had a 1.5 mm control fiber used for 1.5 mm tests, and a 1.2 mm control fiber used for 1.2 mm tests.

We had a startup procedure that was intended to stabilize the PMT after instances where the PMT had been off for several hours or more before the test. Before starting the tests, we had a series of runs where the power supply was on for at least eight minutes total before any measurements were taken. The startup procedure follows:

1. Turn on power supply, wait two minutes, turn off
2. Open box, insert source, shut box, turn power supply on for two minutes, turn power supply off
3. Open the box long enough to take a temperature measurement and then close box, turn on power supply for two minutes, then shut off
4. Repeat step 3
5. Take a pedestal measurement by turning power supply on, wait two minutes, and then starting measurement

This was done to simulate light exposure the PMT undergoes during a test. As for the actual tests, we had a very similar procedure:

1. Place control fiber in the box, close box, turn on power supply, wait two minutes, take measurement, turn off power supply
2. Open box, place test fiber in box, close box
3. Arrange setup for 0 wraps, turn power supply on for two minutes, take measurement, turn off power supply
4. Repeat 3., but for 1 wrap, 2 wraps, $\frac{1}{2}$ wrap, $\frac{1}{4}$ wrap, 0 wraps in that order
5. Repeat 4. as many times as needed
6. Take last measurement with the control fiber

A measurement means 150 instantaneous measurements of the PMT current averaged together over an approximately one minute period of time. This was done to minimize statistical error (.01 nA in every case).

Results

Performing the experiment required measuring the pedestal, measuring current as a function of bending the fiber, and calculating the systematic errors. The pedestal was roughly .5 to .6 nA whereas the signal was on the order of 10 nA. The voltage was set at -1200 volts for the PMT since the pedestal scales much more slowly than signal as one raises the magnitude of the voltage.

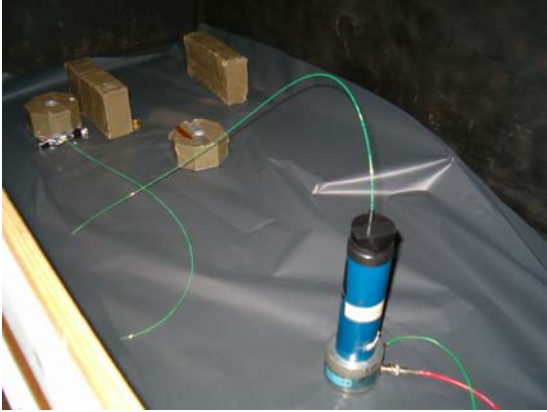


Figure 5. Above Left: The components of the setup, fiber, tile, lead cone, and PMT

Figure 6. Above Right: Fiber inserted into a tile

We studied the following as possible sources of systematic error: the test-to-test variations in high voltage (HV), the slight variations of the pedestal including the effect of cosmic rays and also how the pedestal fluctuates right after the PMT is turned on, the PMT gain versus temperature, the change in efficiency in the PMT over run time, the effect of light from opening the box on the PMT over repeated tests, and the variations from connecting the fiber and wrapping the fiber.

To correct for HV variations we approximated the dependence with an exponential curve fit over a range centered around -1200 V. The imprecision from the curve fit was much less than 0.1% and thus was ignored.

We looked at the effect of cosmic rays on the tests by measuring the pedestal with the fiber inserted into the tile with no source and measuring the pedestal with the fiber pulled out from the tile. The difference between the two values was a .01% effect and therefore ignored.

Another effect we observed was the pedestal decrease after the power supply has been turned on. This is important since the pedestal can be as much as twice as large initially as compared to its value after waiting two minutes after the power supply has been turned on. To minimize this effect, the test procedure always called for a two minute wait before data taking. When doing this, the pedestal never varied more than

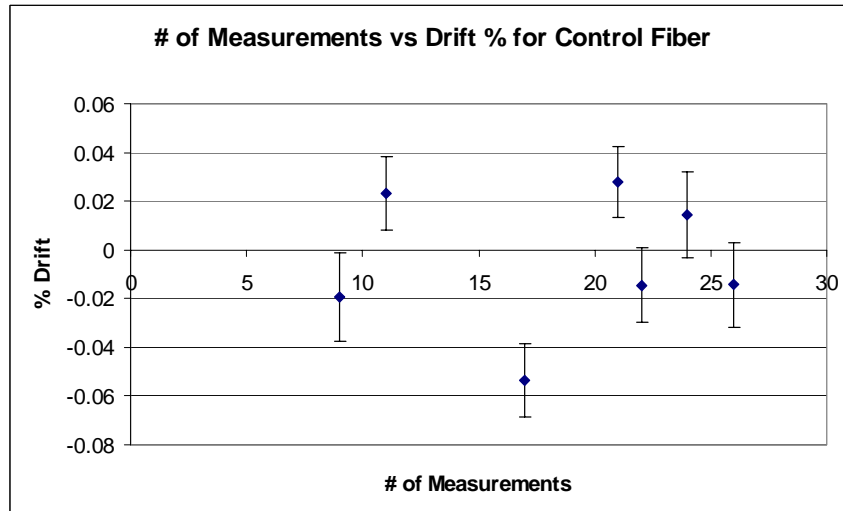
.02% of the actual PMT current. Because it was so constant, we only took one pedestal measurement at the beginning of a run.

The effect of temperature on the PMT given by Hamamatsu engineers is -0.4% per 1°C for anode sensitivity for light in the 200 nm to 550 nm region. No test had a measured temperature variation of more than .5°C, and in most cases the variation was only a few tenths of a degree Celsius. Since measurements of bending the fiber were done by cycling through each variation of wrap before repeating a wrap, time dependent effects should affect all measurements equally. Since temperature effects appear relatively small this effect was ignored.

We also looked for other time dependence in the tests. In nearly every test, we measured control fiber current before and after to get an estimate of the drift during a test. The global error, which is defined in the section describing how we calculated errors in the experiment, was used as the error in the measurements with the control fibers. We looked at dependence of drift versus the number of measurements taken which should give a rough estimate of the duration of a given trial. We found the percent drift defined by this formula.

$$\%Drift = \frac{FirstMeasurement - LastMeasurement}{FirstMeasurement + LastMeasurement}$$

The following graph shows the number of measurements versus the percent drift.



There does not appear to be a clear pattern in drift of measurements over the experiment. However, a χ^2 test of the hypothesis that the above data is consistent with 0

drift gives only 1% probability. If we increase the errors from the experiment by an additional 50%, the χ^2 test would give a 50% probability. This suggests that the uncertainty could be underestimated, but by no more than 50%.

We calculated something we called global error. Global error means the error present in a measurement for any type of wrap around any bend diameter for a given fiber. Our motivation for doing this was to overcome our poor estimates of the error for small diameters of bending. We calculated the errors in the following way. Results for the 4.5" diameter bend and the 3.5" diameter bend (excluding 2 wraps) were taken and the error calculated using the following formula.

$$\sigma_{global} = \sqrt{\frac{1}{N} \sum_j (N_j - j) \sum_i^{N_j} (x_i - \bar{x})^2}$$

N is the number of different wraps, N_j is the number of measurements for a given wrap, and x_{mean} is the mean for a given wrap. We used only 4.5" and 3.5" diameter wraps since there was little light loss for these tests. The error we found was then interpreted as the error for tests of smaller diameters. Note that since the statistical errors were so negligible, the global error is really the systematic error for the experiment.

The results of the tests are summarized in the following tables. In each row, we divided through by the mean PMT current for straight fiber measurements from the test of that particular diameter. The result of dividing through as just described is the fraction of light yield compared to the light yield of unbent fiber.

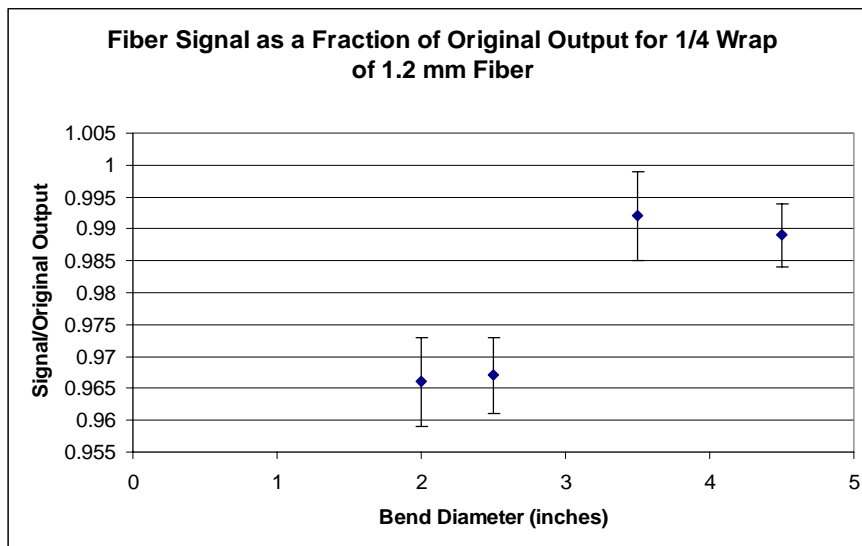
Table 1. Below.

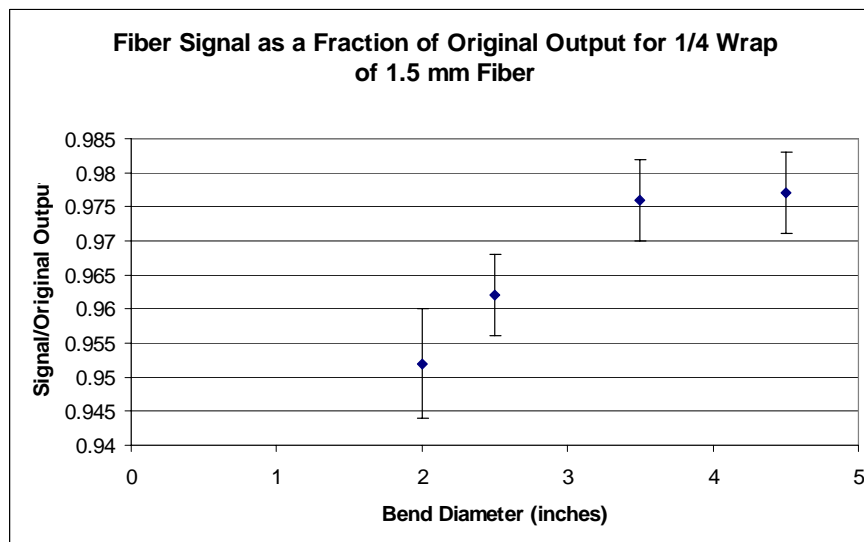
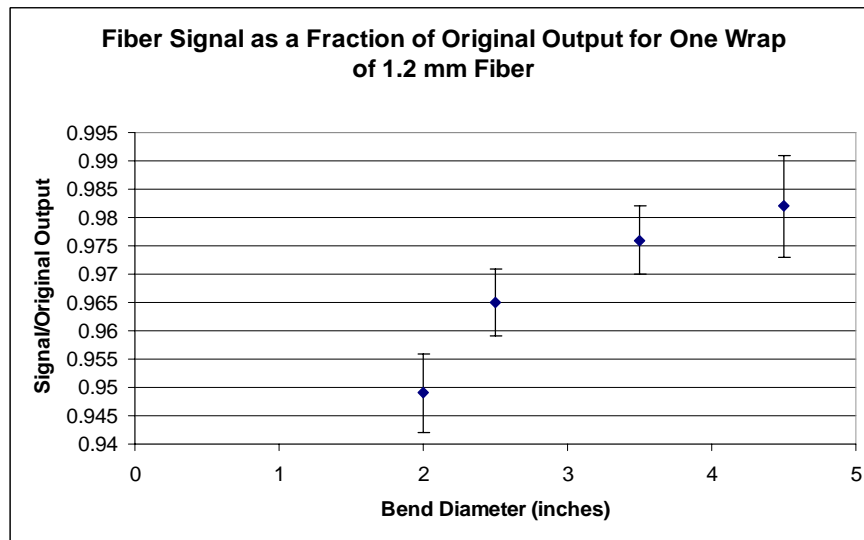
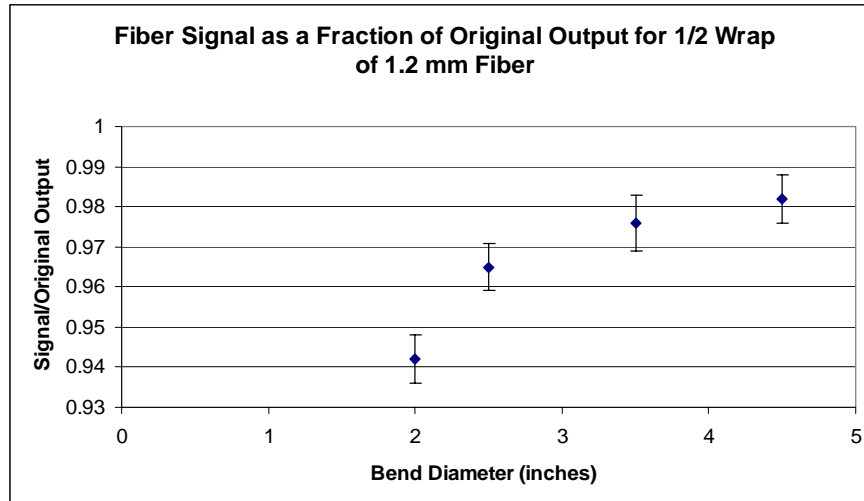
Fraction of original Signal for Different Bend Diameters for 1.2 mm fiber										
	# of Wraps									
Diameter	0	1/4	1/2	1	2	0 error	1/4 error	1/2 error	1 error	2 error
2	1.000	0.966	0.942	0.949	0.919	0.005	0.007	0.006	0.007	0.007
2.5	1.000	0.976	0.971	0.965	0.949	0.004	0.006	0.006	0.006	0.006
3.5	1.000	0.992	0.983	0.976	0.969	0.005	0.007	0.007	0.006	0.006
4.5	1.000	0.989	0.992	0.982	0.971	0.005	0.005	0.006	0.009	0.006

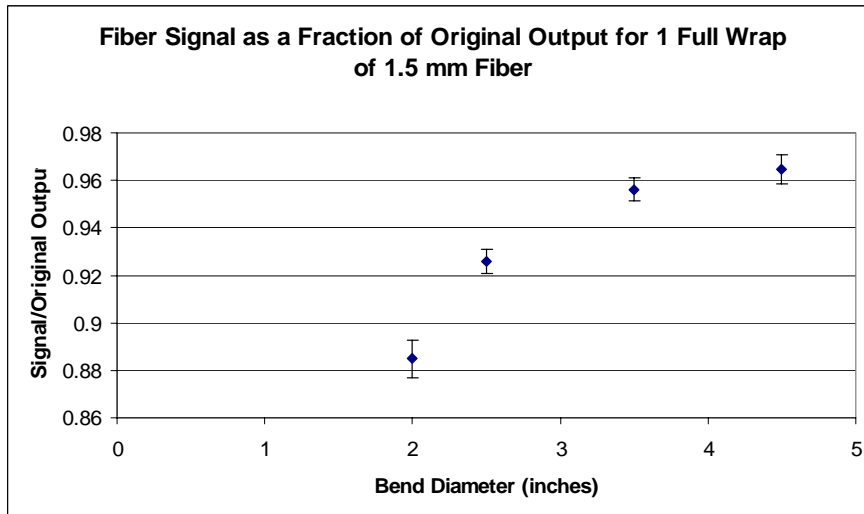
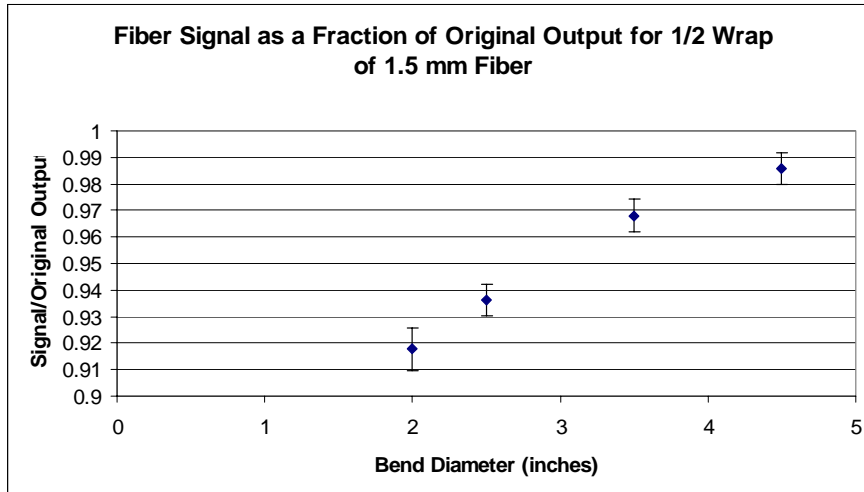
Table 2. Below

Fraction of Original Signal for Different Bend Diameters for 1.5 mm Fiber								
	# of Wraps							
Diameter	0	1/4	1/2	1	0 error	1/4 error	1/2 error	1 error
2	1.000	0.952	0.918	0.885	0.008	0.008	0.008	0.008
2.5	1.000	0.962	0.936	0.926	0.004	0.006	0.006	0.005
3.5	1.000	0.976	0.968	0.956	0.004	0.006	0.006	0.005
4.5	1.000	0.977	0.986	0.965	0.005	0.006	0.006	0.006

Light loss is consistently less for 1.2 mm fiber than 1.5 mm fiber. Plots summarizing the results can be found on the next several pages. The plots look at the scenarios of a full wrap, a half wrap, and a quarter wrap separately. This was done since in actual practice the fiber will most likely not be bent a full wrap, so a variety of wraps were chosen.



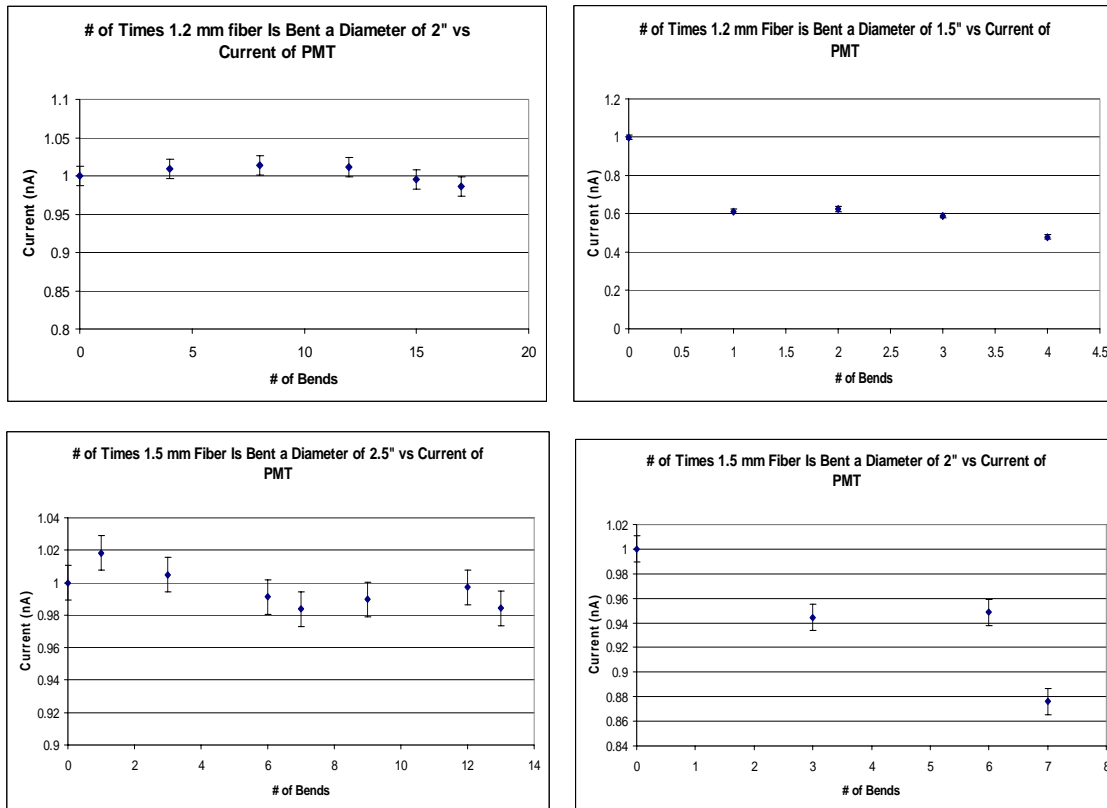




Tests for a bend diameter of 1.5" were done for the 1.2 mm fiber, but reliable numbers are not available since the fiber was cracked during the testing. However, there are qualitative results that came out of attempting to do that measurement and other tests. One point worth noting is that 1.2 mm fiber can be bent around a diameter of 1.5", but problems arise in the act of bending the fiber tightly around the spool. As the fiber is wrapped it forms an oval around the spool and the portion away from the spool cracks as it gets bent locally a tighter diameter than the spool. For 1.5 mm fiber, this same effect occurs at a bend diameter of 2". For diameters 1" and less, the 1.2 mm fiber literally broke. The 1.5 mm fiber cracked severely when attempts were made to bend the fiber to a diameter of 1.5".

We also looked at how the current read out from the PMT using a given fiber decreases as the fiber gets bent a number of times during the tests. We found a decrease

in current as a function of the number of times the fiber is bent. For 3.5" and 4.5" diameter bends, there is very little effect.



For 1.5 mm fiber, we compared PMT current for a 2.5" diameter bend to that of 2" diameter bend. There is a slow decrease in output for the 2.5" diameter bend, but there are larger discontinuous decreases for the 2" diameter bend case. So for the 2.5" diameter case, the fiber is likely undergoing small amounts of damage whereas for the 2" case serious cracks are occurring in the fiber. This is quite a dramatic difference between the two diameters which is why 2.5" bending diameter was selected as the minimum bending diameter for 1.5 mm fiber. For 1.2 mm fiber, we did the same type of comparison, except for 2" bending diameter and 1.5" bending diameter. Once again the smaller bending diameter has large discontinuous drops in output whereas the larger diameter has a more gradual slide in output. This is why 2" was selected as the minimum bending diameter for 1.2 mm fiber.

Some useful rules of thumb were found while working with the fiber. One small crack in a fiber will decrease the light yield of that fiber by at least 10% and likely more.

A severe crack can reduce the light yield by as much as 50%. The difference probably is whether just one layer of cladding was cracked or both layers.

Another qualitative finding is that 1.5 mm fiber is much easier to crack just by simply handling it compared to 1.2 mm fiber. Only several instances of unintentional cracking 1.2 mm fiber occurred while handling it during the tests. But, for 1.5 mm fiber, the fiber was frequently cracked.

Conclusion

The fibers have clear differences. Although 1.5 mm fiber can give higher light yield, it is much easier to break. Limits for bend diameter can be set at 2" for 1.2 mm fiber and 2.5" for 1.5 mm fiber. If such diameters were used some fiber would still get cracked because excess bending locally would inadvertently happen at this range, as it did several times during the tests. The 1.2 mm fiber was much easier to work with and is recommended unless it proves to be an untenable option because of low light yield.

There are several ways the tests can be improved. One is better use of a control fiber. Remembering to take a measurement with the control fiber every time would be a simple improvement. An extension of these tests would be to study the effect of time on different diameter bends. This means wrapping sets of fiber around different diameters and measuring the results every several days. Something of this sort was attempted with the naked eye, but results were too hard to interpret because of the subjective nature of trying to identify cracks in fiber.